Evaluation of Dynamic Bandwidth Allocation with Clustered Routing in FiWi Networks

Yousef Dashti, Anu Mercian, and Martin Reisslein

***Abstract*—The demand for bandwidth in broadband access networks has been increasing exponentially in recent years, due to high-bandwidth applications, such as video on demand (VoD), and peer-to peer (P2P) networking through increasingly powerful mobile devices. The demand for bandwidth and mobility has motivated the development of fiber-wireless (FiWi) networks, which combine the optical access network with the wireless network. FiWi networks support high bandwidth with optical networking mechanisms and mobility through wireless networking. In our previous work, we introduced clustered and localized routing (CluLoR) in FiWi networks. We examined CluLoR, which improves throughput-delay performance compared to a flat (unclustered) topology, only for an elementary dynamic bandwidth allocation (DBA) algorithm in the optical part of the FiWi network. In this paper, we extend our previous work by conducting an extensive evaluation of DBA algorithms on the CluLoR performance in FiWi networks. In this paper, our focus is how the wireless upstream traffic based on CluLoR going into the optical access network performs when conventional wired traffic is included in the optical network. We evaluate the delay performance for different practical scenarios and examine the underloading and overloading of the wireless and wired traffic respectively on FiWi networks. Our evaluations indicate that the performance impact of DBA algorithms depends on the source of the traffic and we provide comparisons in this paper.**

***Index Terms*—Delay evaluation, dynamic bandwidth allocation, excess bandwidth distribution, PON, Fiber-Wireless.**

I. INTRODUCTION

Passive Optical Networks provide high bandwidth capabilities that satisfy the bandwidth-hungry services to end-users. But deployment of fiber to end users incurs high capital (CAPEX) and operational expenditures (OPEX). Thus Fiber-Wireless, an integration of optical fiber infrastructure and wireless access networks has emerged as an attractive approach. Integration of Optical and Wireless Networks is called Radio-over-Fiber (RoF) networks [1]–[3] is one of the first papers that discussed the integration of optical access networks with wireless access network. An earlier test-bed implementation of FiWi in [4]. The Hybrid Wireless Optical Broadband Access Network (WOBAN) is one of the first proposed architectures and the authors discussed different issues such as network setup, routing techniques, and protection techniques to serve against network failure. Another paper that discussed network planning and setups is [5], while [6] provides a recent surveys on FiWi. The paper gave an overall view of the recent architectures deployed for FiWi and provided simulation results to assess the capabilities of these architectures.

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One of the first papers that discussed the Peer-to-Peer (P2P) communications problem in FiWi is [7]. The paper mainly discussed the advantage of integrating the wireless access network with the optical access network in order to achieve better delay-throughput performance for the communicated peers compared to when the peers are just communicating through the wireless access network. Another paper that discussed the P2P communication is [8]. The main contribution of that paper was to have a decentralized Dynamic Bandwidth Allocation (DBA) [9] to support inter-ONU communications. In this case, the traffic does not have to go through the OLT which could lead to a significant improvement in the delay performance. The direct inter-ONU communication is supported through WDM/TDM PON architecture. Other similar studies that support inter-ONU communications are [10], [11] in which a star coupler is deployed at the remote node in order to enable an ONU to broadcast its packets to other ONUs. WDM-EPON that supports inter-ONU communication was proposed in [12]. The proposed technique focuses on diving the polling cycle into two sub cycles.

On of the main challenging problems in FiWi networks is to find an efficient routing protocol to route the traffic between wireless nodes within the wireless network or through the wireless network to the optical network to reach the Internet, example [6], [13]–[16]. Most of the routing protocols that were proposed for FiWi considered flat topology with no clustering structure. In our recent paper, CluLoR [17], we combine clustered scheme with a localized routing scheme which proved to give better overall delay-goodput performance when compared to a routing scheme that focuses on minimum hop-count. Recent work on FiWi networking focuses on green networking and protection techniques in order to have a reliable FiWi network, see e.g., [18]–[20].

In this paper, we simulate a network with a combination of wired and wireless traffic in FiWi Network, introduce a DBA space and qualitatively analyze it, which to the best of our knowledge, has not been extensively analyzed before in literature. An interesting practical application is the Cloud-mobile host implementation, where we have multiple mobile hosts accessing data from Cloud servers. Cloud server are examples of heavily loaded wired networks, and mobile hosts are wireless nodes connected to the gateway at their average data rate. We also analyze the delay performance of different DBAs and propose the usefulness of each DBA for specific scenarios that are of practical importance.

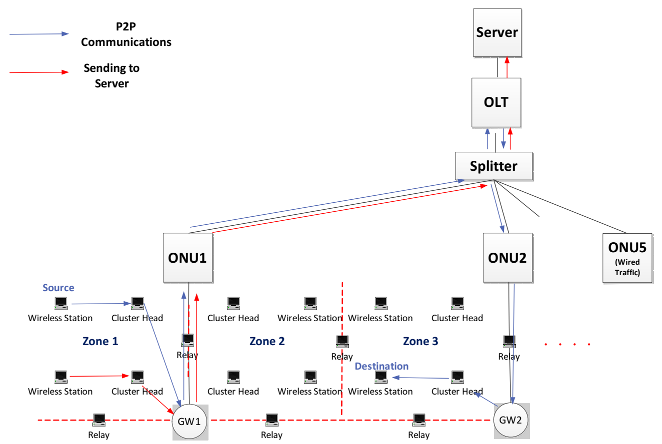


Fig. 1. Architecture set-up of the FiWi Network and illustration of CluLoR routing. The wireless network is organized into zones, each operating at a different frequency. Wireless stations route traffic through a cluster head towards the gateway for transmission over the PON.

II. Clustered Routing and Peer-to-Peer Networking

CluLoR [17] focuses on a localized routing of packets. The wireless network is clustered into zones, where each zone operates on a different radio channel with a possibility of using the same radio channel in a further zone (same concept as frequency reuse). Localized routing of packets is performed through routing the packets to the zone that includes the destination wireless nodes without going through intermediate zones that do not have the destination wireless node in order not to add more interference to the intermediate zone. In this paper, we focus on routing the packets through two heads per zone as it was shown in our previous published paper that it gives the best performance. In this paper, there are two types of destinations, server destination and Peer-to-Peer (P2P) destination. The traffic of the server destination has to go through the cluster heads then routed to the closest gateway router which is turn routes it to the ONU. The ONU then waits for its time share of the upstream bandwidth to send the packet to the OLT and then from the OLT to the server. The P2P communication follows the same routing scheme mentioned in CluLoR. Fig 1 illustrates this routing scheme. For more information, please refer to [17].

III. DBA extension to FiWi Networks

In this section, we introduce dynamic bandwidth allocation (DBAs) for the fiber network and the importance of it when used with wireless network. We introduce a DBA space for the FiWi networks which combines different combination of grant transmission of the fiber network with that of the wireless network. The wired network follows the MPCP protocol (Multi-Point Control Protocol) in a time-sharing basis in the upstream direction and broadcast protocol in the downstream direction as used in IEEE 802.3ah. The MPCP protocol requires REPORT messages to be sent from the ONU to the OLT, with the information of the packets in the queue at the ONU, corresponding to which a GRANT message is sent to the ONU granting the necessary bandwidth to send the queued packets based on specific DBAs [21] . The ONU and Gateway follow a point-to-point (P2P) protocol, and have a duplex mode transmission, thus upstream and downstream transmissions do not collide. The wireless network follows a two-head Cluster Head transmission, as explained in the previous section, in the upstream as well as in the downstream direction. As we illustrate in the table below, the DBA space, which was introduced in [22] for PON, is extended here for FiWi Networks and consists of the following:

- Grant Scheduling Framework – Decides when the grant is scheduled from the OLT to the ONU to allow upstream data transmission.
- Grant Sizing – Determines the amount of GRANT allocated to each ONU.
- Grant Scheduling Policy – Determines the ordering of the ONUs for scheduled payload transmission
- ONU-GW Scheduling – Determines the data transmission from the GW to the ONU and vice versa
- Wireless Scheduling – Method of data transmissions from the wireless stations (WS) to the Gateway.

TABLE I
DBA Space for FiWi Networks

Grant Sched. Framework	Grant Sizing	Grant Sched. Policy	ONU-GW Sched.	Wireless Sched.
Online Offline	Gated Limited Excess	SPD	Periodic	Continuous- With EBO

The wireless nodes, continuously sends traffic upstream to the Gateway (GW) as and when it is generated. If the packet is affected by noise, it follows the basic exponential back-off (EBO) pattern to retransmit the packet. The packets are buffered at the GW until the uplink is free and then the GW sends the buffered packets to the ONU, where they are buffered until the ONU receives GRANT from the OLT. Therefore, the GW-ONU transmission, follows a continuous periodic transmission with a period of the average packet size. The Grant Scheduling Policy follows the shortest propagation delay (SPD) [23] policy, which arranges the ONUs based its shortest distance to OLT.

We experiment a simplified DBA space of the wireless network, by keeping some of the features of the DBA space standard and varying the Grant Scheduling frameworks and Grant Sizing Policy of the DBA Space to analyze the performance of the FiWi Network. We utilize two variations of Grant Scheduling Frameworks:

- Offline - This scheduling framework awaits REPORTs from all ONUs before sending GRANTs to the ONUs. This framework is helpful for sending GRANTs to ONUs in a more intelligent manner based on the requirements of all the other ONUs.
- Online - This scheduling framework sends grants to an ONU immediately after receiving the REPORT from that ONU. This framework does not include the waiting time involved as in the case of Offline technique.

Different Grant sizing policies include:

- Gated – Granting the amount requested by the ONU. If $R(n,j)$ is the requested bandwidth in cycle n by ONU j, then the Grant $G(n,j)$ for cycle n will be:

$$G(n,j) = R(n,j) \tag{1}$$

The disadvantage of the Gated technique is that a single heavily loaded ONU may monopolize the upstream link and this would be unfair to other lightly loaded ONUs.
- Limited – This scheme overcomes the unfair distribution of grant by limiting the maximum grant size that could be given to an ONU. If the ONU requests more than the maximum grant size, then the OLT limits it to the maximum grant size. If the maximum grant size is $G_{\max}$:

$$G(n,j) = \begin{cases} R(n,j) & \text{for } R(n) \leq G_{\max} \\ G_{\max} & \text{for } R(n,j) > G_{\max}. \end{cases} \tag{2}$$

The disadvantages of Limited Grant Sizing are that the heavily loaded ONUs are restricted to send less than they request and that the entire cycle time may not be utilized.
- Excess Bandwidth Grant Sizing – This scheme overcomes the disadvantage of Limited by obtaining the excess bandwidth from the underloaded ONUs and using it for the overloaded ONUs. Therefore, if $R(n,j)$ is less than $G_{\max}$, the ONU is given whatever it requests and the excess is saved into a pool to be used by heavily loaded ONUs. We use equitable excess bandwidth division for our setup, by which we divide the entire pool equally among all the overloaded ONUs.

$$E(n,j) = \sum_j G_{\max} - R(n,j) \text{ if } R(n,j) < G_{\max} \tag{3}$$

$$G(n,j) = \begin{cases} R(n,j) & \text{for } R(n,j) \leq G_{\max} \\ \min\{R(n,j), G_{\max} + \frac{E(n,j)}{O}\} & \text{for } R(n,j) > G_{\max}. \end{cases} \tag{4}$$

From this point, we will be using the terminology, (on.,gat.) for Online, Gated; (on.,lim.) for Online, Limited; (off., lim.) for Offline, Limited; (off.,exc.) for Offline, Excess; for ease of use.

Motivation for DBA in FiWi Network: We now outline the advantage of the extended DBA space for Fiber-Wireless Networks. In our initial analysis with FiWi Network we consider 8 ONUs and assign wireless traffic transmission for 4 ONUs and wired traffic transmission for the remaining 4 ONUs, which we will refer to as FiWi traffic and PON traffic from this point and we observed that the FiWi Network with (on., gat.) DBA gives good result for the PON traffic but does not favor the FiWi traffic. Also, We use the IEEE 802.11g standard which gives a maximum bandwidth of 54 Mbps, but the net bandwidth utility of WLAN of the PON, based on our FiWi configuration described later in this paper, we observe a net bandwidth utility of 28 Mbps. Thus indicating that the ONUs connected to the WLAN are lightly-loaded. This is our motivation to experiment DBAs that can utilize the excess bandwidth of the FiWi traffic to use for the PON traffic that generally overloads the network for high loads.

IV. Description of Simulation Setup

We use OMNet++ 4.2.2 [24], using INETMANET-2.2 modules, with a self-built eponsim module to simulate FiWi Network. In this work we are simulating a network that consists of two types of traffic, PON traffic and FiWi traffic going into the optical network to reach a server outside the optical network or to reach a destination peer within the wireless part of the network. Our network consists of 8 ONUs, where 4 ONUs mainly serve FiWi traffic while the other 4 ONUs are connected directly to traffic generators that send PON traffic upstream to the OLT. For the first 4 ONUs that are connected to wireless domain, the routing of the traffic is based on CluLoR [17] with two cluster heads serving each zone.

There are 64 wireless nodes that are uniformly distributed in an area of 1000 m $\times$ 1600 m. The distance between two neighboring wireless nodes is set to 100 m. There are a total of 16 zones (each zone has 4 wireless nodes), where each zone operates on a different radio channel and the zones that are further away would reuse some of the radio channels in order to minimize the interference. This due to the fact that IEEE802.11g has 11 different radio channels only. A Gateway router serves 4 zones in order to route its traffic to/from the optical network. Thus, the gateway router is equipped with 4 different radio channels. The ethernet cable connecting the gateway router to the ONU has a transmission rate of 1Gbps. Between adjacent zones, a relay router is placed, equipped with two different radio channels to relay the traffic between adjacent zones, instead of sending traffic through the PON.

The other 4 ONUs that are connected to PON traffic would only route the traffic in the upstream direction of the optical network. The ratio between the incoming PON traffic to the traffic coming from a gateway router that serves the wireless domain is 30:1, this is to maintain the PON traffic ONUs overloaded and the FiWi traffic ONUs lightly loaded, such that maximum Fiber utility does not exceed a capacity of 1 Gbps. All the traffic in simulation are based on UDP.

The ONUs are placed uniformly at a distance of 15 km to 20 km from the OLT. FiWi traffic is also routed to a server that is connected to the OLT, in which the OLT would route some of its incoming FiWi traffic to the server. In the wireless domain, we use a channel model that is based on a distance path loss channel with alpha value set at 2. The signal-to-noise ratio is set at 4 dB (a received packet is considered noise if its received value is below the threshold) while the radio sensitivity is set at -85 dBm. The transmission power for the wireless nodes in each zone is set at 20mW, which is enough for the farthest wireless node in a zone to reach the gateway router (The transmission rate is around 250m). The wireless LAN retransmit limit follows the IEEE802.11g standard which is set at a default value of 7. The physical data rate of the wireless nodes is set at 54 Mbps. The buffer size of the wireless LAN is set at 1000 packets regardless of the size of the packets and follow a Drop Tail Queue distribution.

In our simulation we employ quad mode packet size distribution with 60% 64 byte packets, 4% 300 byte packets, 11% 580 byte packets and 25% 1518 byte packet. For the initially generated payload sizes, UDP application header of 8 bytes, IP header of 20 bytes, and MAC level header of 18 bytes (included at the Ethernet level) are all appended to the original payload as the packet enters the optical network. The maximum transmission unit (MTU) for the wireless nodes is set at 1500 in order to avoid fragmentation. The generated traffic follows an independent Poisson Process, in which all the wireless nodes have the same mean value of packet generation. The collected results of the simulations are based on a confidence level of 95%. Simulation results are collected until the buffer overflows, as beyond this, packets are lost and delay is increased exponentially, this is the reason, some of the delay results are terminated earlier than the other one. In our simulations, we are collecting the mean end-to-end delays. Two different delays are considered:

- End-to-end delay for the PON traffic
- End-to-end delay to reach the server (FiWi traffic)

A. Description of Network Scenario

We simulate two scenarios for the FiWi traffic, while the PON traffic is sent in the upstream direction to the OLT in both cases. We experiment with different DBAs for both scenarios to observe effects on different FiWi traffic models, as our emphasis is on DBA utility for FiWi Networks.

a) Scenario 1: In this scenario, the cluster heads send their generated traffic in the upstream direction to the optical network to reach the server (destination of packets). Other wireless stations send their generated traffic to wireless nodes with equal probability within the wireless domain, including the cluster heads (P2P communications). The routing follows CluLoR.

b) Scenario 2: In the second scenario, both the cluster head and the wireless station traffic is routed to the server. The DBA scheme used in this part of the simulation is gated online scheme. Here, most of the traffic is directed only upstream.

For our DBA Impact analysis, we select Scenario 2 for extensive analysis. We found in preliminary evaluations that it gives the lowest delay performance with a classic DBA, such as (on., gat.), as it deals with only upstream traffic and will be a good reference curve and also due to space restrictions.

V. Performance Evaluation

A. Preliminary Considerations

As for the mean end-to-end delay for the packets to reach the server, two scenarios were considered as mentioned above. Factors that affects the delay values are the number of hops a packet needs to travel to get to the server, and the queueing delay of cluster heads especially if most of the traffic has to go through the cluster head. The traffic can be outgoing traffic of the zone or incoming traffic to the zone since some peers are communicating with each other. Having incoming and outgoing traffic in a scenario would lead to higher interference and packet collisions in a zone which causes some of the wireless nodes to send their packets multiple times to reach the next node. Higher interference and packet collisions would lead increase the queue of the cluster heads and cause buffer overflow.

The cycle time equation for FiWi network can be given as:

$$Z = O(2\tau_P + t_G + 2t_C + t_g), \quad (5)$$

where Z is the cycle time, τ_P is the propagation time for the PON Network, t_G is the average Grant size allocated for the ONUs in that cycle, t_C is the transmission time of the Control message (REPORT and GRANT), and t_g is the guard time.

While the PON is covering the Z cycle time, correspondingly multiple cycles of data transmission from Gateway to the OLT with average cycle period of 493.7 bytes and with the overhead about 511.7 bytes for the quad mode packet distribution and from the wireless station to the Gateway are simultaneously occurring. These transmission are masked in the cycle time as the links can work in parallel. Based on the cycle time equation, for $Z = 2$ ms, we receive a Grant size (in bytes) of 28142 bytes (or $t_G = 0.22$ ms)for each ONU. Although the ONUs connected to the wireless stations can go upto a maximum of $G_{\max}$ of 28142 bytes, the wireless loads almost never reach this load value in most practical scenarios due to its net utility capacity.

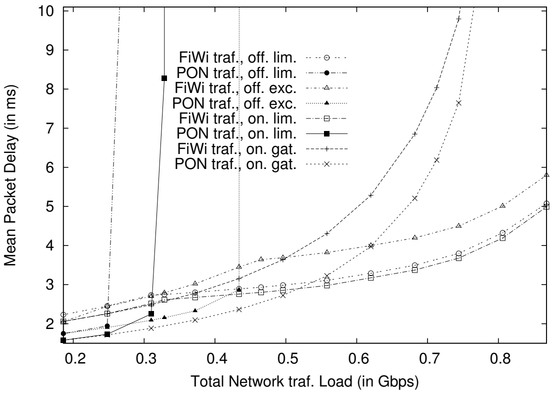
As we mentioned the incoming traffic ratio into the ONUs is 1:30 (FiWi traffic:PON traffic). Based on that it is clear that the first 4 ONUs that are serving the FiWi traffic are lightly loaded when compared to the second 4 ONUs that serve PON traffic.

B. Impact of DBA

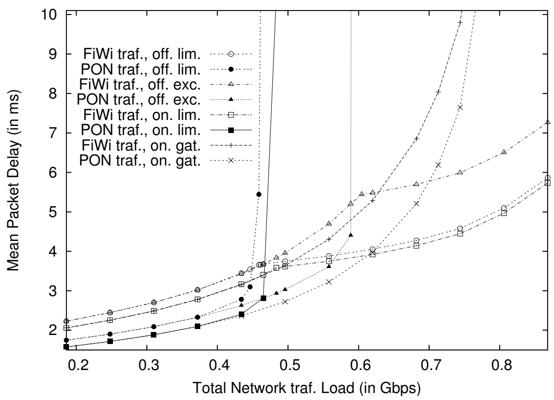
1) Online, Gated: In the (on., gat.) scheme, we observe the delay curves are exponential. This reflects that the Gated algorithm that grants the ONU, an amount equal to the request. This is beneficial for PON traffic which dominates the network with increasing overall traffic load. However, the heavy PON traffic load increases the delay of the FiWi traffic, which has to wait longer for the start of the next cycle. The (on., gat.) scheme is not cycle time dependent and hence has been repeated in Fig. 2 (a), (b), and (c) as it acts as the reference curve for all DBAs. For PON traffic, this scheme gives the best delay performance and the lowest delay performance for FiWi traffic.

2) Offline, Limited: As seen in Fig. 2, offline, limited (offl., lim) works in favor of FiWi traffic, compared to (on., gat.). Fixing the cycle time ensures that the lightly loaded FiWi traffic ONUs) transmit frequently and do not have to wait until the PON traffic ONUs transmits their entire queues. This is disadvantageous for the heavily loaded PON traffic ONUs, whose requests are limited. With further increasing load, the queue continuously builds up and results in buffer overflow. The load point where buffer overflows for PON traffic occur indicate the stability limit in our simulations. Average packet delays grow very high near and beyond the stability limit.

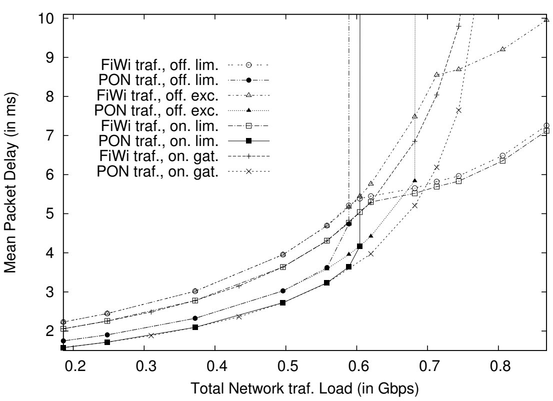
Contrastingly, for the FiWi traffic, we observe that (off., lim.) is advantageous, as by limiting the heavily loaded PON traffic ONUs, we are limiting the cycle time and therefore reducing the queueing time for the FiWi traffic packets. We observe a “knee point” of the FiWi traffic delay near the load level corresponding to the stability limit for the PON traffic. Once the PON traffic queues fill up and the PON



a) SCN 2, with cycle time $Z = 1$ ms



b) SCN 2, with cycle time $Z = 2$ ms



c) SCN 2, with cycle time $Z = 4$ ms

Fig. 2. Avg. delay for different DBAs for Scenario 2 for three different avg. cycle time ranges, to compare the stability limit of each.

traffic completely utilizes its limited share of the cycle time, no further increases in the carried upstream load are possible due to PON traffic. Instead, further increases in the carried upstream traffic load are due to FiWi traffic only, which follows the fixed 1:30 PON:FiWi traffic ratio. That is, only 1/30 of a given increase in the total traffic load contributes to the actual increase of the carried upstream traffic load. This "switch" from all generated traffic contributing to the carried upstream traffic load to only 1/30 of the generated traffic load contributing to the carried upstream traffic load results in the substantially lower slope of delay increases with increasing generated traffic load, i.e., the observed "knee point".

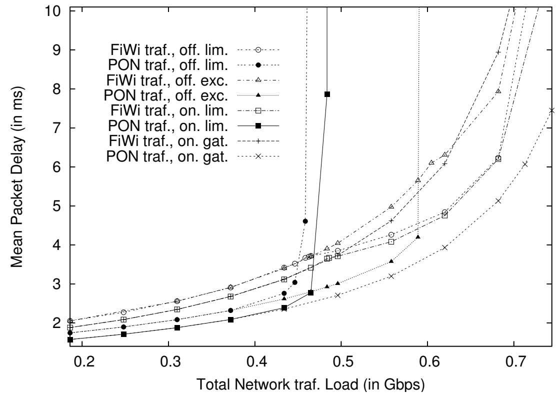


Fig. 3. Average Delay Performance for Scenario 1 for different DBAs for cycle time $Z = 2$ ms

3) Online, Limited: Online, limited (onl., lim.) follows the same performance trend as of the (offl., lim), while performing slightly better than (offl., lim.). This is because of the offline framework [9], [22], which waits for all the REPORTs from the ONUs before sending the GRANT messages. This delay difference is small because only 8 ONUs are considered. As the number of ONUs increases, this delay value would also increase.

For FiWi traffic, (on., lim.) is also better than (off., lim.) because of reduced waiting time for the REPORTs at the OLT. The trend that can be observed is that online scheduling framework is better than offline framework for both PON and FiWi traffic in general. The trend of the FiWi traffic experiencing a reduced slope of delay increases (knee point) after the stability limit of the PON traffic has been reached can be seen in this case as well.

4) Offline, Excess: For the (off. exc.) scheme, we observe that for low loads, the delay for the PON traffic is the same as for (off., lim.). This is because, all ONUs are underloaded at low loads and do not require the excess feature. However, as the load values increase, the delay of (off., exc.) is lower than (off., lim.), and (offl. exc.) reaches an almost 30 % higher stability limit.

In case of the FiWi traffic, (off., exc.) delay is higher than (off., lim.) delay. This is due to the increase in average cycle time as the overloaded ONUs connected to PON traffic take longer to send the excess grants. Thus, FiWi traffic is queued longer at the ONUs before receiving the grant for the next cycle. The (off., lim.) scheme performs about 18% better than (offl., exc.) at high loads.

5) DBA Impact for Scenario 1: Scenario 1 experiences incoming traffic within the zones because of P2P communication, thus more interference and collisions is introduced to the zones, causing the wireless nodes to resend the traffic more frequently than in scenario 2. The retransmissions cause the packets to queue up and therefore buffer overflow occurs at lower loads compared to scenario 2. This is shown in Fig 3, as the maximum network traffic load we simulated was lower than in scenario 2, since there is no point to simulate the network when buffer overflow occurs in the wireless domain and maintain the 1:30 traffic ratio.

C. Impact of Average Cycle Time (Z)

Depending on the cycle time limit, the stability limit occurs at different network loads. Having longer cycle times relieve the PON traffic ONUs from infinite buffer delay, which in turn shows the improvement of delay performance. For FiWi traffic, impact of cycle time is, the lower the stability limit for the PON traffic, lesser the delay due to lower granting delay.

For example, the Stability limit for the PON traffic for (on., lim.) for $Z = 1$ ms in Fig 2 (a) is 0.330 Gbps, $Z = 2$ ms in Fig 2 (b) is about 0.485 Gbps which is almost similar to (off., lim.), and $Z = 4$ ms in Fig 2 (c) is 0.620 Gbps. Thus, the stability limit is also better for (on., lim.) by sending the GRANT immediately after the REPORT messages. Observing the PON traffic, As in the case of (off., lim.), for cycle time $Z = 1$ ms in Fig 2 (a), we see that the stability limit is around 0.31 Gbps, and for $Z = 2$ ms in Fig 2 (b), about 0.46 Gbps and for $Z = 4$ ms in Fig 2 (c), it is about 0.595 Gbps. For lower cycle time, the $G_{\max}$ would be lower thus, reducing the stability limit. For (off., exc.) stability limit for $Z = 1$ ms in Fig 2 (a) is 0.465 Gbps, $Z = 2$ ms in Fig 2 (b) is about 0.6 Gbps, and $Z = 4$ ms in Fig 2 (c) is 0.713 Gbps.

Considering the improvement of the stability limit for (off., exc.) in comparison to (on., lim.), we see that there is an 40 % improvement for $Z = 1$ ms, about 25 % for $Z = 2$ ms, and about 15 % for $Z = 4$ ms. As the cycle time increases, the relative improvement decreases, thus the improvement with (off., exc.) is especially pronounced for short cycle times.

VI. Conclusion

We conclude that for a FiWi network with a mix of PON-only traffic traversing only the fiber (wired) PON part of the network and FiWi traffic traversing both the wireless and (potentially) the fiber part of the FiWi network, gated dynamic bandwidth allocation (DBA) serves the PON-only traffic well at the expense of relatively high delays for the FiWi traffic. DBAs with bandwidth limits mitigate the performance degradation for the FiWi traffic even for high PON-only traffic loads. The offline DBA with excess bandwidth distribution emerged as the most efficient DBA for a network with PON and FiWi traffic, as the portions of the upstream transmission cycle not utilized by FiWi traffic can be used for carrying heavy PON traffic loads.

In future work, we plan to examine DBA in long-range FiWi (LR-FiWi), where the distance between the OLT and ONU can be on the order of 100 km [25]. This would also provide the platform to experiment with advanced DBAs, such Multi-Thread Polling [26] and Double-Phase Polling [27].

References

[1] N. Ghazisaidi, M. Maier, and C. M. Assi, "Fiber-wireless (FiWi) access networks: A survey," *IEEE Comm. Mag.*, vol. 47, no. 2, pp. 160–167, 2009.

[2] M. Maier, N. Ghazisaidi, and M. Reisslein, "The Audacity of Fiber-Wireless (FiWi) Networks," in *Proc. of AccessNets*, ser. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering. Springer, 2009, vol. 6, pp. 16–35.

[3] S. Sarkar, S. Dixit, and B. Mukherjee, "Hybrid wireless-optical broadband-access network (WOBAN): A review of relevant challenges," *IEEE/OSA J. Lightwave Techn.*, vol. 25, no. 11, pp. 3329–3340, 2007.

[4] H. Izadpanah, D. Gregoire, F. Dolezal, W. Ng, D. Yap, and G. Tangonan, "An integrated fiber optics/broadband wireless access demonstrator for the next generation internet (NGI) network extension," in *Proc. Int. Topical Meeting on Microwave Photonics MWP*, 2000, pp. 172–174.

[5] Y. Liu, C. Zhou, and Y. Cheng, "S^2U: An efficient algorithm for optimal integrated points placement in hybrid optical-wireless access networks,," *Computer Communications*, vol. 34, no. 11, pp. 1375–1388, 2011.

[6] W.-T. Shaw, S.-W. Wong, N. Cheng, K. Balasubramanian, X. Zhu, M. Maier, and L. G. Kazovsky, "Hybrid architecture and integrated routing in a scalable optical wireless access network," *IEEE/OSA J. Lightwave Techn.*, vol. 25, no. 11, pp. 3443–3451, 2007.

[7] Z. Zheng, J. Wang, and J. Wang, "A study of network throughput gain in optical-wireless (FiWi) networks subject to peer-to-peer communications," in *Proc. IEEE ICC*, 2009, pp. 1–6.

[8] Y. Li, J. Wang, C. Qiao, A. Gumaste, Y. Xu, and Y. Xu, "Integrated fiber-wireless (FiWi) access networks supporting inter-ONU communications," *IEEE J. Lightw. Techn.*, vol. 28, no. 5, pp. 714–724, 2010.

[9] J. Zheng and H. Mouftah, "A survey of dynamic bandwidth allocation algorithms for Ethernet Passive Optical Networks," *Optical Switching and Netw.*, vol. 6, no. 3, pp. 151–162, Jul. 2009.

[10] N. Nadarajah, M. Attygalle, A. Nirmalathas, and E. Wong, "A novel local area network emulation technique on passive optical networks," *IEEE Photonics Techn. Letters*, vol. 17, no. 5, pp. 1121–1123, 2005.

[11] A. V. Tran, C.-J. Chae, and R. S. Tucker, "Bandwidth-efficient PON system from broadband access and local customer internetworking," *IEEE Photonics Technology Letters*, vol. 18, no. 5, pp. 670–672, 2006.

[12] W.-R. Chang, H.-T. Lin, S.-J. Hong, and C.-L. Lai, "A novel WDM EPON architecture with wavelength spatial reuse in high-speed access networks," in *Proc. IEEE ICON*, 2007, pp. 155–160.

[13] X. Shao, Y. K. Yeo, L. H. Ngoh, X. Cheng, W. Rong, and L. Zhou, "Availability-aware routing for large-scale hybrid wireless-optical broadband access network," in *Proc. OFC*, 2010, p. JThA42.

[14] F. Aurzada, M. Lévesque, M. Maier, and M. Reisslein, "FiWi access networks based on next-generation PON and gigabit-class WLAN technologies: A capacity and delay analysis," *IEEE Trans. Netw.*, 2014.

[15] F. Aurzada, M. Scheutzow, M. Reisslein, N. Ghazisaidi, and M. Maier, "Capacity and delay analysis of next-generation passive optical networks (NG-PONs)," *IEEE Trans. Comm.*, vol. 59, no. 5, pp. 1378–1388, 2011.

[16] S. Cho, S. Ramasubramanian, O. Turkcu, and S. Subramaniam, "Throughput and delay analysis of multi-channel wireless infrastructure networks," *Ad Hoc Networks*, vol. 10, no. 3, pp. 373–387, 2012.

[17] Y. Dashti and M. Reisslein, "CluLoR: Clustered localized routing for fiwi networks," *Journal of Networks*, 2014.

[18] B. Kantarci and H. T. Mouftah, "Energy efficiency in the extended-reach fiber wireless access networks," *IEEE Netw.*, vol. 26, no. 2, pp. 28–35, 2012.

[19] M. Maier, "Survivability techniques for NG-PONs and FiWi access networks," in *Proc. IEEE ICC*, 2012, pp. 6214–6219.

[20] Y. Liu, Q. Song, R. Ma, B. Li, and B. Gong, "Protection based on backup radios and backup fibers for survivable fiber-wireless (FiWi) access network," *Journal of Network and Computer Applications*, vol. 36, no. 3, pp. 1057–1069, 2013.

[21] A. Mercian, M. P. McGarry, and M. Reisslein, "Impact of report message scheduling (RMS) in 1G/10G EPON and GPON," *Optical Switching and Networking*, vol. 12, pp. 1–13, 2014.

[22] M. P. McGarry and M. Reisslein, "Investigation of the DBA algorithm design space for EPONs," *IEEE/OSA J. Lightwave Techn.*, vol. 30, no. 14, pp. 2271–2280, 2012.

[23] M. McGarry, M. Reisslein, F. Aurzada, and M. Scheutzow, "Shortest propagation delay (SPD) first scheduling for EPONs with heterogeneous propagation delays," *IEEE JSAC*, vol. 28, no. 6, pp. 849–862, Aug 2010.

[24] O. www.omnetpp.org.

[25] B. Skubic, J. Chen, J. Ahmed, B. Chen, L. Wosinska, and B. Mukherjee, "Dynamic bandwidth allocation for long-reach PON: overcoming performance degradation," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 100–108, 2010.

[26] A. Mercian, M. McGarry, and M. Reisslein, "Offline and online multi-thread polling in long-reach PONs: A critical evaluation," *IEEE/OSA J. Lightwave Techn.*, vol. 31, no. 12, pp. 2018–2028, 2013.

[27] S. Choi, S. Lee, T.-J. Lee, M. Y. Chung, and H. Choo, "Double-phase polling algorithm based on partitioned ONU subgroups for high utilization in EPONs," *IEEE/OSA J. Opt Commun. Netw.*, vol. 1, no. 5, pp. 484–497, 2009.